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# Evidence based survey of the distribution volume of ethanol; comparison of empirically determined values with anthropometric measures

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## Highlights

- Blood-alcohol calculations are often required in forensic science casework, they commonly used the Widmark equation.
- Anthropometric equations can tailor Widmark's rho-factor for a given individual.
- Results using anthropometric equations were in reasonably good agreement with rho-factors determined empirically.
- A regression equation involving the person's age, height and body weight was the best model for male subjects.
- Consideration of the person's BMI gave more accurate results for females.

## Abstract

The Widmark equation is commonly used when blood alcohol calculations are required in forensic and legal medicine, such as in road-traffic cases and alcohol-related deaths. An important biological variable in this connection is the volume of distribution ($V_d$) of ethanol, which is commonly referred to as the rho-factor. Although a person's $V_d$ can be determined empirically through controlled drinking experiments, this approach is not very practical in reality. For this reason, a number of anthropometric equations have been developed that utilize sex, age, height and weight to estimate the person's total body water (TBW) and hence $V_d$ of ethanol. To date, there aren't any studies that compare $V_d$ derived from anthropometric data with

robust values measured empirically. From the literature we compiled information about the $V_d$ of ethanol from drinking studies with 173 Caucasian males and 63 Caucasian females from Western Europe. These empirically derived values of $V_d$ were then compared with estimates derived from various anthropometric equations. In males the Watson, Watson and Batt regression equation involving age, height and weight gave the most accurate results (bias was 0.00 L/Kg) and 95% confidence limits (CI) were ± 0.13 L/Kg. The equation derived by Forrest, which took into consideration a person's body mass index (BMI), gave the best estimates of $V_d$ for females; mean bias -0.01 L/Kg and 95% CI ± 0.15 L/Kg.

**Keywords**

Blood-alcohol, BMI, ethanol, drunken driving, volume of distribution, rho factor, total body water, Widmark equation.

## 1. Introduction

In medico-legal casework it is not always possible to obtain a sample of blood at the time of an alleged offence, such as in sexual assault crimes or drink-driving cases. Nevertheless, expert witnesses are often asked to calculate a suspect's blood alcohol concentration (BAC) at the material time of the alleged offence/incident. In such calculations, knowledge of the pharmacokinetics of ethanol is important, especially the volume of distribution ($V_d$) and the rate of ethanol elimination from the bloodstream.

Professor Erik Widmark (1889-1945) was the first to study the pharmacokinetics of ethanol in the 1930s [1]. His experiments were carried out under strictly controlled conditions in healthy subjects, who drank a moderate dose of ethanol as neat spirits on an empty stomach. Under these drinking conditions the bioavailability of orally administered ethanol is close to 100%. Evidence for this comes from dilution experiments in which ethanol was used to determine total body water (TBW). The values obtained showed a good agreement with TBW determined by isotope dilution experiments [2,3].

The volume of distribution ($V_d$) of a drug is a theoretical volume into which the entire dose is distributed to give the same concentration as in the blood. The $V_d$ will depend on the physicochemical properties of the drug, such as its relative solubility in lipids and water, the degree of protein binding as well as other factors. Also important for $V_d$ is the person's age, sex and adiposity [4]. Widmark derived an

equation to calculate the total amount of alcohol absorbed and distributed in all body fluids and tissue from the concentration determined in a sample of blood (see equation 1), which is still widely used in forensic science and legal medicine:

$$C_o = \frac{100 \times A}{Weight \times r} \quad (1)$$

In the above equation, r = volume of distribution ($V_d$) commonly known as Widmark's rho-factor in units of L/Kg, $C_o$ = the concentration of ethanol in blood at the time of starting to drink (mg/100 mL), A = amount of alcohol (ethanol) in grams distributed in TBW and Weight = the person's body weight (kg). The factor 100 is necessary to convert BAC in g/L to mg/100 mL, the unit used in UK for legal purposes.

According to Widmark's research, the average rho factor for healthy men (n = 20) was 0.68 compared with 0.55 for females (n = 10) [5]. Ethanol is a drug that distributes into the TBW compartment, without binding to plasma protein and the solubility of ethanol in lipids is negligible compared with the water solubility of ethanol. The rho factor is therefore closely related to the person's TBW and the latter can be used to derive the $V_d$ of ethanol provided water content of blood is taken into consideration.

In 1981 Watson, Watson and Batt [6] updated the Widmark equation in an attempt to derive more reliable values of the rho-factor based on a person's age, body weight and height. They presented multiple regression equations for a large number of male and female subjects that determined the person's TBW. In this way the rho-factors were tailored for that particular individual. Various other methods are available to determine the Widmark rho-factor based on anthropometric data and measures of body fat and obesity [7–9].

The aim of this study was to determine, using a single data set, the accuracy and precision of the various equations available to derive the Widmark rho-factor. These include papers by Watson *et al*. [6], Forrest [9], Ulrich *et al.* [8], Seidl *et al.* [7] and Maudens *et al* [10]. In some legal jurisdictions fixed values for $V_d$ are used, such as 0.70 L/Kg for adult non-obese men and 0.60 L/Kg for non-obese women.

## 2. Materials and Methods

The gold standard method to determine the Widmark rho-factor ($V_d$) requires carefully controlled drinking experiments [12]. The test subjects consume ethanol as neat spirits as a bolus dose and on an empty stomach. After the end of drinking a sufficient number of blood samples are then taken for quantitative analysis of ethanol so that the absorption, distribution and elimination phases of the BAC curve are defined with certainty. The BACs on the post-absorptive elimination phase are then

used to derive the y-intercept ($C_0$), which is incorporated into equation 1 to calculate the Widmark rho-factor.

Figure 1 shows a typical concentration-time profile of ethanol in one male subject who consumed an ethanol dose of 0.68 g/kg as neat whisky on an empty stomach. The most important parameter is $C_o$ (theoretical blood alcohol concentration at time zero (start of drinking), which represents the theoretical BAC if the entire ethanol dose was absorbed and distributed throughout the TBW. Likewise, the $C_{max}$ (the maximal concentration of ethanol reached in blood) is marked on the graph as well as the equation to calculate $V_d$ from dose (g/kg) divided by $C_o$.

Figure 1 here

In human dosing studies of this kind, it is important that ethanol is consumed as neat spirits on an empty stomach (overnight fast). Alternatively, the dose of ethanol could be given intravenously to ensure a bioavailability of 100%. Administration of alcohol with food leads to abnormally high rho-factors, because of first-pass metabolism in gastric mucosa and/or the liver [11]. The repetitive blood samples should, whenever possible, be taken at 15-30 min intervals and cover the entire declining phase of the BAC profile [12].

### 2.1 Study Search and Inclusion Criteria

The literature search strategy was conducted according to the methodology of the 2009 PRISMA statement [13]. The literature search was performed using Google Scholar, PubMed and SCOPUS databases. The references retrieved were then hand-searched for additional references. The following keywords in titles and abstracts were used: (ethanol) AND (ingestion OR blood OR subject* OR calculation* OR Widmark OR metabolism). (alcohol) AND (ingestion OR blood OR subject* OR calculation* OR Widmark OR metabolism). The search was limited to articles published in English. The databases were searched from inception to 24$^{th}$ July 2017. The asterisk (*) allows for “wildcard” searching around the term it is attached to. Additionally, the Journal “Blutalkohol” was searched manually from its inception (1961) to May 2017.

For inclusion in our dataset, the experimental design in the publication needed to conform to the following criteria: -

1) Oral administration of a moderate dose of ethanol.
2) Alcohol consumed on an empty stomach after an overnight fast and in a short period of time (<20 minutes).
3) Alcohol concentrations determined in blood samples.
4) Blood samples taken at a frequency sufficient to plot the entire C-T profile and to determine $C_o$ using validated methodology.

5) The study chosen needed to include information about age, sex, weight, height, $V_d$ and the dose of ethanol administered to each individual.

The literature search identified 5 articles fulfilling the above criteria [10,14–17]. Additional C-T data was made available from the article by Gullberg and Jones [18] and re-worked for purposes of the present article to determine $C_o$ and $V_d$ for each subject by linear regression of the BAC vs time in the post-absorptive phase.

The comprehensive study by Alha [15], although published in 1951, was useful because it involved a large number of drinking subjects and increasing doses of ethanol (0.5-1.25 g/kg). Some drinking experiments were done on the same individual on different occasions, which furnished information about within-subject variation in the rho-factor. Under these circumstances, an average rho-factor was calculated for each subject and used to construct the box-and-whisker plots shown in figure 2, section 3.1.

Overall, this retrospective study included ethanol pharmacokinetic data for 233 healthy Caucasian subjects comprised of 173 males and 63 females.

### 2.2 Total Body Water Equations

The anthropometric equations used to determine TBW and hence the Widmark rho-factors are detailed below.

#### 2.2.1 Widmark's rho-factor

The mean experimentally determined values from the complete data set (173 men and 63 women) were used as the empirically derived rho-factors; 0.70 L/kg for men and 0.60 L/kg for women. We also used the factors originally determined by Widmark (0.68 for males and 0.55 for females), because these values are still used in some jurisdictions.

#### 2.2.2 Watson, Watson and Batt method of estimating the rho-factor

The Watson, Watson and Batt equation was modified according to Gabe [19], who suggested using a weight/volume ratio of the blood water content, namely 0.84 g/100 mL (rather than the weight/weight value of 0.80 g/100 g used by Watson *et al.* [6])

$$\mathrm{r\,(male)} = \frac{2.447 - (0.09516 \times Age) + (0.1074 \times Height) + (0.3362 \times Weight)}{Weight \times 0.84} \qquad (2)$$

$$\text{r (female)} = \frac{-2.097 + (0.1069 \times \text{Height}) + (0.2466 \times \text{Weight})}{Weight \times 0.84} \quad (3)$$

Weight (kg), height (cm), age (years), r (L/kg).

Watson and colleagues also provided a method of calculating r when information about a person's height was unavailable.

$$\text{r (male)} = \frac{20.03 - (0.1183 \times Age) + (0.3626 \times Weight)}{Weight \times 0.84} \quad (4)$$

$$\text{r (female)} = \frac{14.46 + (0.2549 \times Weight)}{Weight \times 0.84} \quad (5)$$

Weight (kg), Age (years), r (L/kg)

### 2.2.3 Forrest method of estimating the rho-factor

As with the Watson method, the calculations done by Forrest [9] were modified to incorporate weight/volume for whole blood (0.84 g/100 mL). The following equations combine the three-step approach described by Forrest into a single calculation.

$$\text{r (male)} = \frac{0.724 \times \left((\text{Weight}) - ((((1.34 \times \text{BMI}) - 12.467)/100) \times Weight)\right)}{Weight \times 0.84} \quad (6)$$

$$\text{r (female)} = \frac{0.724 \times \left((\text{Weight}) - ((((1.371 \times \text{BMI}) - 3.467)/100) \times Weight)\right)}{Weight \times 0.84} \quad (7)$$

Weight (kg), BMI = Body Mass Index (kg/m$^2$), r (L/kg)

### 2.2.4 Ulrich *et al.* method of estimating the rho-factor

The alcohol dosing studies reported by Ulrich *et al*. only involved male subjects so there is no equation for females [8].

$$\mathrm{r\ (male)} = \ 0.715 - (0.00462 \times Weight) + (0.0022 \times Height) \qquad (8)$$

Weight (kg), Height (cm), r (L/kg)

### 2.2.5 Seidl *et al.* method of estimating the rho-factor

Seidl *et al.* developed a new equation for calculating the rho-factor based on the subject's body weight and height and measuring TBW by a bioelectric impedance method. The equations derived from this work were validated by controlled drinking experiments with a smaller group of male and female subjects [7].

$$\mathrm{r\ (male)} = \ 0.31608 - (0.004821 \times Weight) + (0.004632 \times Height) \qquad (9)$$

$$\mathrm{r\ (female)} = \ 0.31223 - (0.006446 \times Weight) + (0.004466 \times Height) \qquad (10)$$

Weight (kg), Height (cm), r (L/kg)

### 2.2.6 Maudens *et al.* method of estimating the rho-factor

Investigators from Belgium determined the $V_d$ of ethanol for males and females in controlled drinking studies for subjects with a much wider range of BMI (16-36 kg/m$^2$) than previous studies. This study is particularly useful considering the changing body composition in today's society with more people being diagnosed as being clinically obese. The article by Maudens *et al.* [10] gave the following equations for the calculation of the Widmark rho-factor.

$$\mathrm{r\ (male)} = \ 0.8202 \ - \ (0.0090 \times BMI) \qquad (11)$$

$$\mathrm{r\ (female)} = 0.7772 \ - \ (0.0099 \times BMI) \qquad (12)$$

Body Mass Index (kg/m$^2$), r (L/kg)

### 2.3 Statistical analysis

Different statistical methods were used depending on characteristics of the various datasets and whether these were normally distributed or not. All the information was

entered into an Excel file (Microsoft (MS) Corporation, Redmond, USA). Distribution volumes of ethanol ($V_d$ or rho) were calculated using equations 2-12 defined above.

SPSS 23 (IBM, New York, USA) was used to test the datasets for normality by inspection of the histograms and use of a Shapiro-Wilks test. Normality was then verified using an Anderson-Darling hypothesis test, which is available in MS Excel [20].

Sex differences in anthropometric variables and mean $V_d$ of ethanol from the empirical studies were compared by use of a Student's independent t-test. Differences between the empirically derived $V_d$ and values based on anthropometric measurements were evaluated by a Student paired t-test and the mean difference tested whether it differed significantly from zero ($\alpha$=0.05). The dataset for females was not normally distributed, so a non-parametric Wilcoxon signed rank test was used to make the same comparison ($\alpha$=0.05).

Confidence intervals (68%, 95% and 99%) were calculated using GraphPad Prism V 6.01 (GraphPad Software, California, USA). Box-and-Whisker plots of frequency distributions were done using MedCalc V18 (MedCalc Software, Ostend, Belgium).

## 3. Results

This study determined, using a single data set compiled from 6 published studies [10,14–18], the accuracy and precision of the various equations available to derive the Widmark rho-factor (Watson et al. [6], Forrest [9], Ulrich et al. [8], Seidl et al. [7] and Maudens et al [10]).

### 3.1 Subject demographics

The mean (± standard deviation (SD)) age, body weight (Wt), height (Ht), body mass index (BMI) for 173 male and 63 female subjects are shown in table 1**,** along with the rho-factors derived empirically from controlled alcohol dosing studies. As expected from previous studies the empirically determined $V_d$ for ethanol varied between individuals and was lower in females compared with males ($p<0.001$). The mean (± SD) values were 0.69 ± 0.086 L/Kg, with a coefficient of variation of 12.41% in 173 males and 0.60 ± 0.100 L/Kg, coefficient of variation of 16.6% in 63 females.

Table 1 here

The frequency distributions of the rho-factors (figure 2) were normally distributed for both men and women as demonstrated by histograms and q-q plots of the data and confirmed by hypothesis tests Shapiro Wilks test and Anderson Darling test (Male: SW (173) = 0.992; p= 0.963 and AD = 0.281; p = 0.639: Females SW (63) = 0.992; p= 0.947 and AD = 0.143; p=0.971).

Figure 2 here

The information presented in table 1 was used to calculate confidence limits on the Widmark rho-factor; 68% CI, 95% CI and 99% CI. For male subjects these CI ranged from 0.66-0.73 L/Kg, 0.55-0.83 L/Kg and 0.43-0.94 L/Kg, respectively. For the females the corresponding CI's ranged from 0.55-0.65 L/Kg, 0.43-0.77 L/Kg and 0.39-0.86 L/Kg, respectively. These ranges were similar to values previously reported by others [12].

The alcohol dosing studies used to derive the rho-factors were published between 1944 and 2014 and all subjects were Caucasians and their ethnicity was Western European. The subjects in the studies were described as fit and healthy, although no other medical health information was provided.

### 3.2 Differences between estimated $V_d$ and empirically measured $V_d$

Divergences between the estimated and empirically derived rho-factors ($V_d$) are plotted in figure 3 and 4 for male and female subjects, respectively. The box and whisker plots show the median values and upper (75%) and lower (25%) quartiles as well as the lowest and highest values. The plots show that use of certain anthropometric equations give closer agreement with empirically measured mean values of $V_d$ than others.

Figure 3 and 4 here

### 3.3 Percentage of subjects with calculated $V_d$ within certain percentage points from the empirical values.

Another way to illustrate the accuracy of the predicted $V_d$ is to calculate the number of subjects that fall within ±5%, ±10% and ±15% of the $V_d$ calculated empirically. Table 2 presents this information for both male and female subjects. On average 37.4 ± 12.9% of males and 35.1 ± 5.0 % of females had an estimated $V_d$ within 5% of the empirically determined values. These percentages increased to 72.1 ± 15.0% for males and 74.0 ± 8.2% for females when ±15% agreement was considered.

Table 2 here

Within the limits of ±5% to ±15% the Watson *et al.* equation (Age, Ht & Wt) gave the most accurate results (males 51.1- 85.8%; females 39.7- 82.5%). Overall these results favour use Watson *et al.* regression equations when a person's $V_d$ for ethanol is derived from anthropometric data in both male and female subjects.

### 3.4 Confidence intervals for difference between estimated $V_d$ and empirically determined values.

Table 3 shows the mean bias (± SD) along with the 68%, 95% and 99% range of values for a single new observation of ethanol $V_d$ for each of the anthropometric methods. Depending on the method used, the mean $V_d$ can be corrected by adding or subtracting the bias shown in table 3.

Table 3 here

## 4. Forensic case example using the results from our study.

The principles outlined in this article for use in forensic blood alcohol calculations can be illustrated by the following example. This assumes a male person aged 50 y (body weight 90.6 kg, and height of 1.81 m), who drank two pints beer (4 vol% or 4% alcohol by volume (ABV)). Alcohol percent by volume is first converted to percent by weight using a density of ethanol of 0.789 g/mL (4 ABV = 3.16 g/100 mL). One UK pint = 568 ml and two pints = 1136 mL so the man has consumed 35.9 g pure ethanol.

Using the Forrest equation for males one gets an average $V_d$ of 0.65 L/Kg for this person. However, according to table 5 the Forrest method has a bias of 0.01 L/kg, which needs to be added to give the corrected value of $V_d$ of 0.66 L/kg (0.65 + 0.01). Table 5 also gives information about the 68%, 95% and 99% ranges of values of $V_d$ for the various equations. In the case of the Forrest method the 95% limits are ± 0.13 L/kg, which means there is a 1 in 40 chance that this man's $V_d$ is lower than 0.52 L/kg (0.65 - 0.13) and a 1 in 40 chance that it is higher than 0.78 L/kg (0.65 + 0.13). Table 4 A also reports the mean bias and the 68%, 95% and 99% range of values of $V_d$ for the other anthropometric equations.

Table 4 A here

Equation 1 can be used to calculate the theoretical BAC ($C_o$) using the mean $V_d$ derived by the Forrest method of 0.66 L/kg and lower and upper 95% limits of 0.52 L/kg and 0.78 L/kg. respectively. The 90.6 kg male drank two pints of 4 vol% beer (35.9 g ethanol), so $C_o$ is calculated to be 60 mg/100 mL with a 95% range from 50-75 mg/100 mL. The results from use of the other anthropometric methods are shown in table 4 B.

Table 4 B here

The choice of whether 68%, 95%, or 99% limits are used will depend on the particular type of forensic case, such where the burden of proof rests. Whether "balance of probabilities" or "preponderance of the evidence" as in civil cases or "beyond a reasonable doubt" as in criminal cases [21,22]. In all forensic work, it is important to remember the philosophy *in dubio pro reo* ("[when] in doubt, for the accused") or basically that the accused should be given any benefit of the doubt. In law a person is presumed innocent until proven guilty.

If the person's $V_d$ is overestimated the value of $C_o$ is underestimated, which would favour the prosecution case in, for example, a post-incident drinking scenario ("hip flask defence"). However, the equations used should be as accurate (and precise) as possible and provide the most unbiased estimates of $V_d$ and $C_o$.

It is important to note that when a range of $V_d$ is calculated, one needs to use common sense, because it is physiologically unlikely that $V_d$ would ever be less than

0.40 L/Kg or higher than 0.85 L/Kg [23]. We therefore suggest that values outside this range should not be considered.

## 5. Discussion

In this article, we have tested the reliability of various indirect methods to estimate the $V_d$ of ethanol by use of anthropometric measures to determine TBW. After a critical review of a large number of human alcohol dosing studies, we selected data from 236 drinking experiments involving 173 men and 63 women and tabulated the Widmark rho-factors. All the articles relied upon appeared in international peer reviewed journals.

In some studies the authors used evidential breath alcohol instruments to plot C-T profiles of ethanol for pharmacokinetic evaluation, such as the one reported by Cowan et al [24]. Use of breath alcohol instruments involves certain assumption about the blood/breath ratio of alcohol and there is no international consensus on the best value to use. When statutory breath-alcohol limits for driving were introduced values of the blood/breath ratios of alcohol varied from 2000:1 to 2400:1 [25]. This makes it difficult to compare venous BAC with breath-alcohol in any individual case [26].

Using the results of the present study, forensic practitioners can select the most appropriate equation to use in the calculation of $V_d$ when they are required to perform certain blood-alcohol calculations in forensic casework.

### 5.1 Study Limitations

There are various limitations to this study that should be mentioned and discussed. First, all the drinking subjects were Western European and Caucasians, mainly those with normal BMI and no overt obesity or malnutrition. To the best of our knowledge none were body builders or suffered from medical problems. However, our material did include a small number of underweight subjects (BMI <18.5. Male n = 3, female n = 1). Furthermore, a number of subjects were clinically obese (BMI >30, female n = 9; male n = 7). Future investigations should try to include subjects with a wider range of BMI, such as those scheduled for gastric bypass surgery for obesity. However, BMI and body fat does not increase linearly with total body water [27]. Other factors

that might influence TBW include malnutrition, dehydration, kidney dysfuntion, such as in dialysis patients, as well as enhanced muscle mass in professional athletes [28,29]. People medicated with diuretic drugs or have liver cirrhosis and ascities or oedema are also likely to have abnormal TBW and consequetly a wider range of ethnaol $V_d$ compared with health individuals.

We were careful to use pharmacokientic studies in which the ethanol was consumed on an empty stomach (overnight fast), because under these conditions bioavailability of the ethanol dose is close to 100%. We have not considered the so-called resorption deficit [7], which basically assumes that a small percentage of the alcohol ingested fails to reach the systemic circulation (blood-stream). It is well known food in the stomach, certain drugs and also medical procedures (such as gastric surgery) can alter the bioavailability of ethanol [4]. In certain German speaking countries when blood-alcohol calculations are made a standard practice is to make an allowance for a resorption deficit, which usually amounts to ~10% of the dose administered [7]. It is also possible that race and ethnicity impact on body composition and TBW, which would be useful to investigate [30–32].

## 6. Conclusions

The results from the present study seem to favour the anthropometric equations published by Forrest [9] and Watson et al. [6] when $V_d$ for ethanol is calcuated rather than the static $V_d$ of 0.70 L/Kg for men and 0.60 L/kg for women derived by Widmark. For male subjects the Watson et al. equation involving age, body weight and height gave the most accurate and precise results. In females the Forrest equation gave the most accurate and precise results followed by the Watson *et al.,* (Height and Weight) equation.

We hope that this article might serve as a primer for use by forensic practitioners and others, when required to perform various BAC calculations or to testify in court as expert witnesses in road-traffic, date-rape or other alcohol-related crimes

Author Contributions (CRediT Statement; https://casrai.org/credit/)

| | |
|---|---|
| Peter D Maskell | Conceptualization, Methodology, Formal Analysis, Project Administration, Validation, Visualisation, Writing – Original Draft, Writing - Review & Editing |
| Anne Savage | Formal Analysis, Validation, Writing - Review & Editing |
| A Wayne Jones | Formal Analysis, Visualization, Writing - Review & Editing |
| Michael Scott-Ham | Conceptualization, Methodology, Writing - Review & Editing |

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**Figure 1:** Typical pharmacokinetic profile of ethanol showing the initial rising blood alcohol concentration (absorption) to reach a maximum concentration ($C_{max}$). This is followed by the elimination of ethanol (zero-order kinetics). Linear regression allows the experimental determination of the blood ethanol concentration at time zero ($C_o$). The volume of distribution ($V_d$) can be calculated in an individual as long as the dose of ethanol and the $C_o$ are known. The concentration-time data used to construct this figure came from reference [18] and illustrates a male subject and 0.68 g/kg of ethanol consumed on an empty stomach in 20 min.

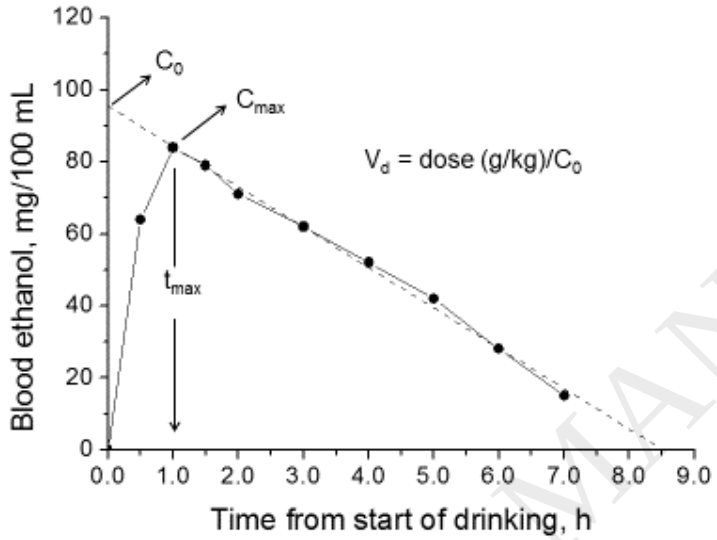


**Figure 2:** Box-and-whiskers plots showing the frequency distributions of Widmark's rho factor ($V_d$ for ethanol) in males (n=173) and females (n=63) derived from controlled drinking experiments [10,14–17].

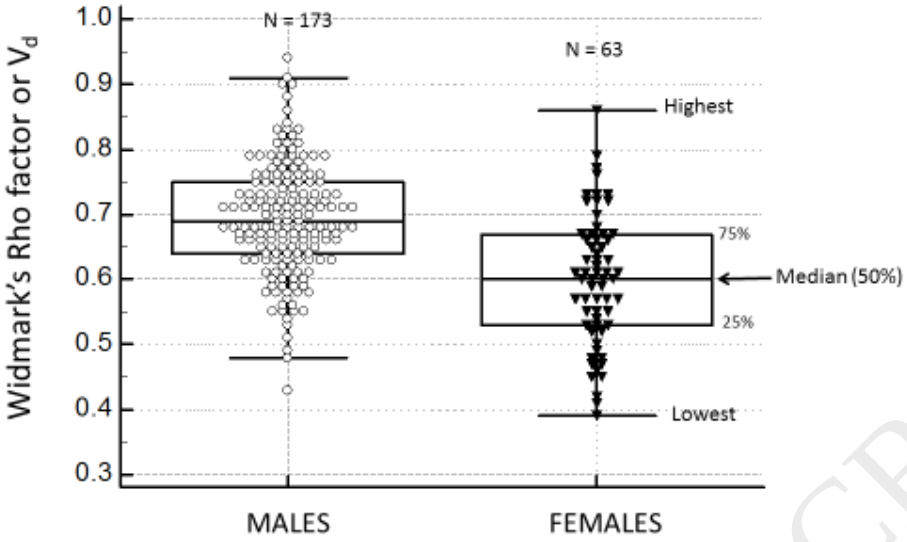

**Figure 3:** Divergences between the estimated (e) and the empirically measured (m) volume of distribution ($V_d$) of ethanol in men (n = 173) using eight anthropometric equations. Mean, 25$^{th}$ and 75$^{th}$ percentiles, maximum and minimum values are shown.

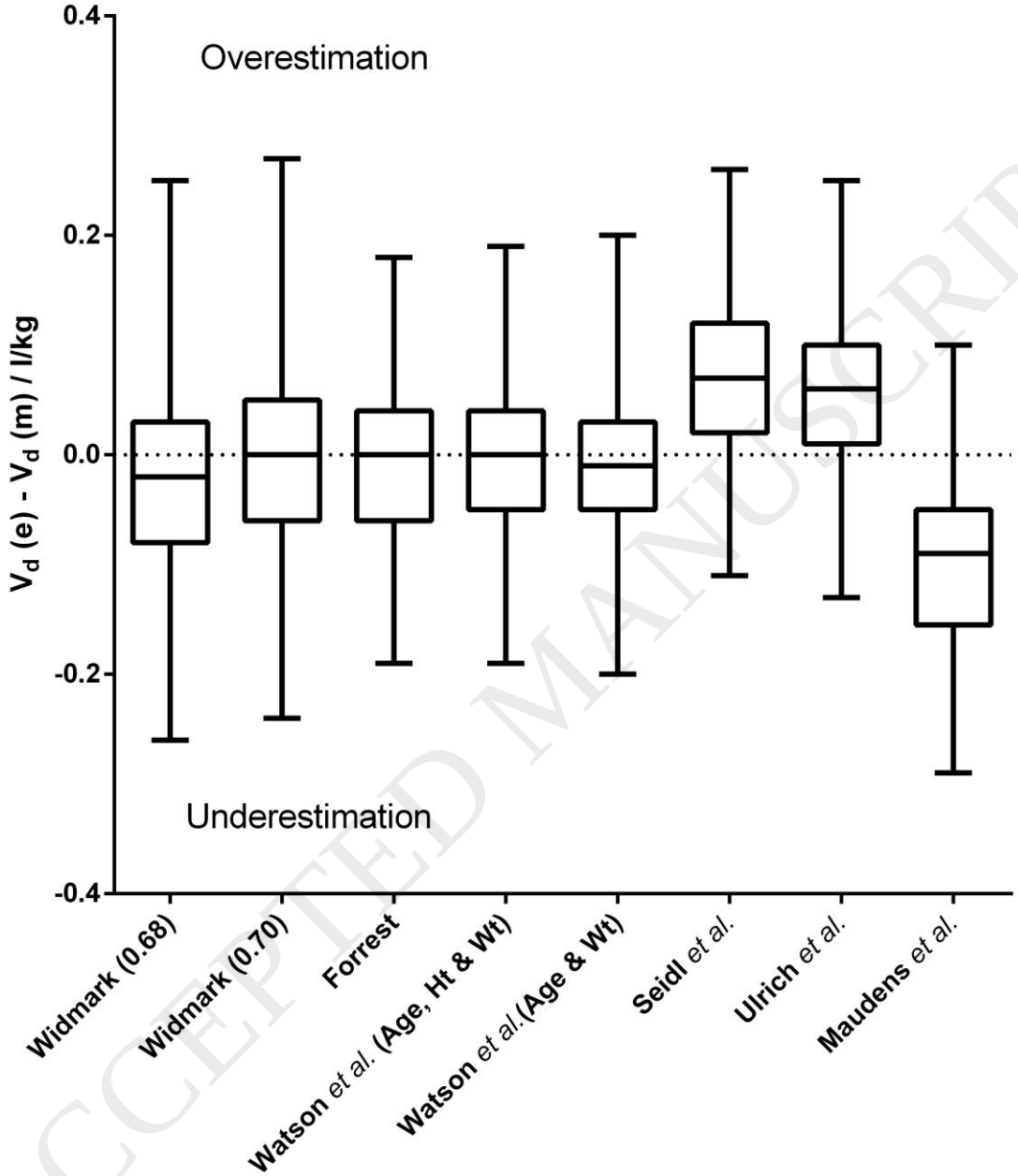

**Figure 4:** Divergences between the estimated (e) and empirically measured (m) volume of distribution ($V_d$) of ethanol in women (n = 63) using seven anthropometric equations. Mean, 25$^{th}$ and 75$^{th}$ percentiles, maximum and minimum values are shown (n = 63).

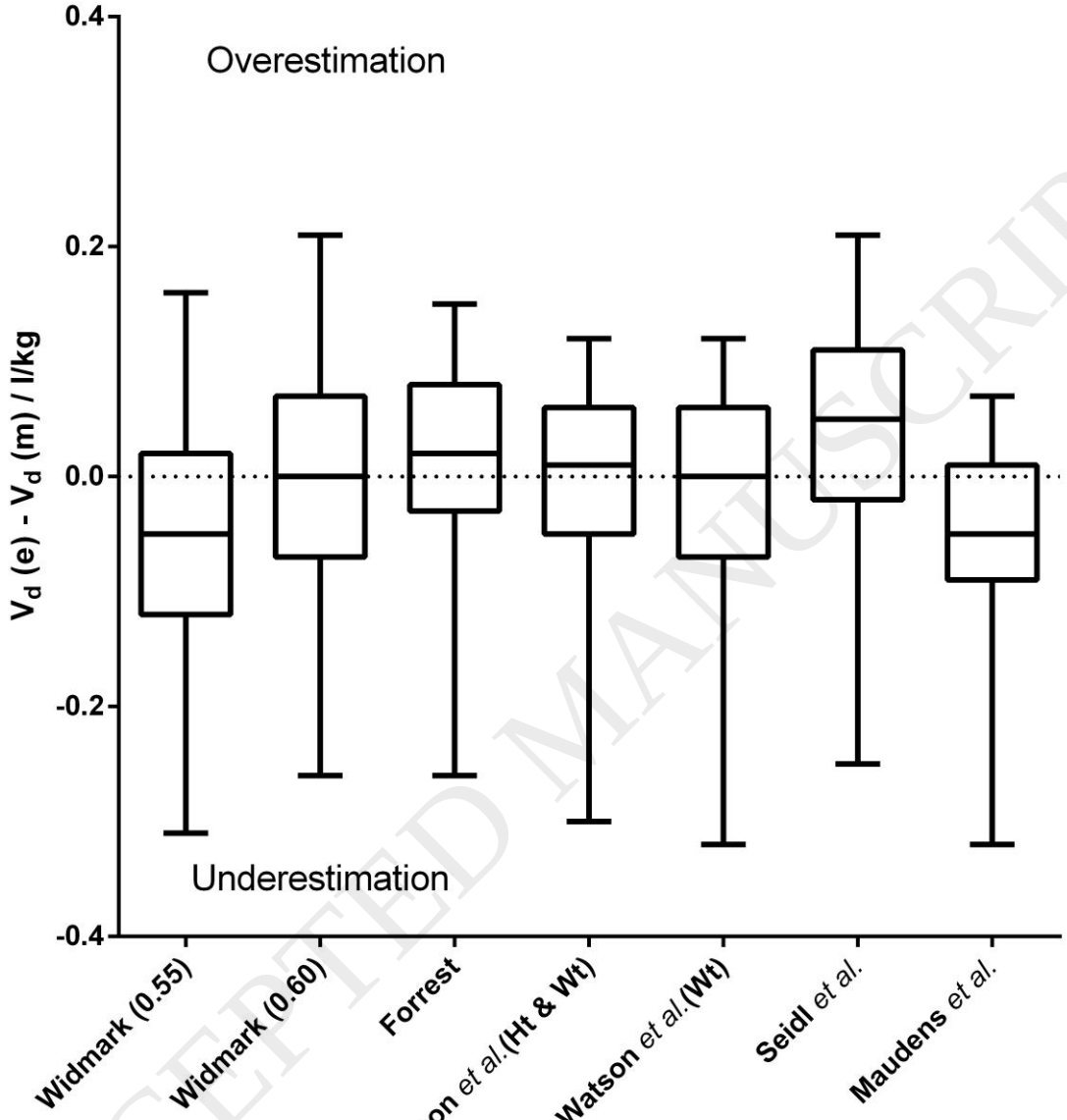

**Table 1:** Summary statistics for anthropometric data (age, body weight and height), body mass index (BMI) and volume of distribution. The statistical significance of sex differences was tested by Student's independent t-test (SD = standard deviation).

| Parameter | Males (n = 173) | | | Females (n = 63) | | |
|---|---|---|---|---|---|---|
| | Mean ± SD | Minimum | Maximum | Mean ± SD | Minimum | Maximum |
| Age (years) | 32.6 ± 10.84[1] | 19.0 | 71.0 | 35.4 ± 14.07 | 18.0 | 70.0 |
| Height (cm) | 176.5 ± 7.10[2] | 160.0 | 196.0 | 164.2 ± 6.68 | 150.0 | 180.0 |
| Weight (kg) | 74.9 ± 11.51[2] | 50.5 | 126.5 | 63.7 ± 14.86 | 42.5 | 108.5 |
| BMI ($kg/m^2$) | 24.0 ± 3.00[1] | 17.8 | 34.9 | 23.6 ± 5.21 | 16.5 | 38.5 |
| $V_d$ (L/Kg) | 0.69 ± 0.086[2] | 0.43 | 0.94 | 0.60 ± 0.100 | 0.39 | 0.86 |

[1] No statistically significant sex difference in mean age or BMI of subjects ($p>0.05$).

[2] Statistically significant sex difference in mean height, body weight and $V_d$ of subjects ($p<0.001$).

Table 2: Percentages of subjects with predicted volume of distribution ($V_d$) of ethanol within ±5%, ±10%, and ±15% of the values determined empirically.

| Method | Males | | | Females | | |
|---|---|---|---|---|---|---|
| | Percent of subjects within ± 5% | Percent of subjects within ± 10% | Percent of subjects within ± 15% | Percent of subjects within ± 5% | Percent of subjects within ± 10% | Percent of subjects within ± 15% |
| Widmark (♂ 0.68; ♀ 0.55) | 41.2 | 59.7 | 74.7 | 25.4 | 47.6 | 65.1 |
| Widmark (♂ 0.70; ♀ 0.60) | 43.8 | 63.5 | 79.8 | 34.9 | 57.1 | 66.7 |
| Forrest | 47.2 | 66.5 | 84.5 | 33.3 | 58.7 | 81.0 |
| Watson (♂ Age, Ht & Wt; ♀ Ht &Wt) | 51.1 | 71.7 | 85.8 | 39.7 | 61.9 | 82.5 |
| Watson (♂ Age & Wt; ♀ Wt) | 50.6 | 51.5 | 85.4 | 44.4 | 52.4 | 81.0 |
| Seidl *et al.* | 30.5 | 51.5 | 71.2 | 34.9 | 52.4 | 66.7 |
| Ulrich *et al.* | 36.9 | 29.6 | 76.8 | ** | ** | ** |
| Maudens *et al.* | 17.6 | 37.3 | 56.2 | 41.3 | 61.9 | 76.2 |
| Mean | 39.9 | 53.9 | 76.8 | 36.3 | 56.0 | 74.2 |
| Standard deviation | 11.4 | 15.5 | 909 | 6.2 | 5.4 | 7.8 |

Table 3: Suggested "correction" factors (bias) for $V_d$ calculated by the various anthropometric methods described in the text.

| Method | Males (n = 173) | | | | Females (males n = 63) | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean ± SD bias in $V_d$ | 68% range (min, max) | 95% range (min, max) | 99% range (min, max) | Mean ± SD bias in $V_d$ | 68% range (min, max) | 95% range (min, max) | 99% range (min, max) |
| Widmark (♂ 0.68, ♀ 0.55) | 0.02 ± 0.085[1] | -0.01 0.06 | -0.12 0.14 | -0.20 0.23 | 0.05 ±0.100[1] | 0.00 0.10 | -0.12 0.22 | -0.16 0.31 |
| Widmark (♂0.70, ♀ 0.60) | 0.00 ± 0.085 | -0.03 0.04 | -0.14 0.12 | -0.22 0.21 | 0.00 ± 0.100 | -0.05 0.05 | -0.17 0.17 | -0.21 0.26 |
| Forrest | 0.01 ± 0.075 | -0.02 0.05 | -0.13 0.13 | -0.17 0.19 | -0.01 ± 0.087 | -0.07 0.01 | -0.13 0.17 | -0.15 0.26 |
| Watson (♂ Age, Ht, Wt, and ♀ Ht and Wt) | 0.00 ± 0.072 | -0.02 0.04 | -0.14 0.12 | -0.17 0.17 | 0.01 ± 0.089 | -0.05 0.04 | -0.11 0.18 | -0.12 0.30 |
| Watson (♂ Age,Wt and ♀ Wt) | 0.01 ± 0.073 | -0.02 0.04 | -0.13 0.13 | -0.17 0.18 | 0.01 ± 0.090 | -0.04 0.04 | -0.11 0.20 | -0.12 0.32 |
| Seidl et al. | -0.07 ± 0.075[1] | -0.10 -0.04 | -0.20 0.06 | -0.26 0.09 | -0.04 ± 0.097[1] | -0.09 0.01 | -0.17 0.15 | -0.21 0.25 |
| Ulrich et al. | -0.06 ± 0.075[1] | -0.08 -0.02 | -0.19 0.07 | -0.24 0.11 | ** | ** ** | ** ** | ** ** |
| Maudens et al. | 0.10 ± 0.076[1] | 0.07 0.13 | -0.04 0.22 | -0.09 0.28 | 0.06 ± 0.086[1] | 0.00 0.09 | -0.07 0.23 | -0.07 0.32 |

[1] The mean difference between $V_d$ estimated from anthropometric data and values measured empirically were statistically significant ($p<0.05$).

Table 4 A**:** Example of a forensic case assuming a 50 y male, body weight 90.6 kg and a height of 1.81 m. Results marked (c) were capped (see text) as they were above 0.85 L/Kg.

| Method | Calculated $V_d$ (L/Kg) | 68% range (L/Kg) (Min, Max) | | 95% range (L/Kg) (Min, Max) | | 99% range (L/Kg) (Min, Max) | |
|---|---|---|---|---|---|---|---|
| Widmark (0.68) | 0.70 | 0.67 | 0.74 | 0.56 | 0.82 | 0.48 | 0.85 (c) |
| Widmark (0.70) | 0.70 | 0.67 | 0.74 | 0.56 | 0.82 | 0.48 | 0.85 (c) |
| Forrest | 0.66 | 0.63 | 0.70 | 0.52 | 0.78 | 0.48 | 0.84 |
| Watson (Age, Ht & Wt) | 0.63 | 0.61 | 0.67 | 0.49 | 0.75 | 0.45 | 0.79 |
| Watson (Age & Wt) | 0.62 | 0.60 | 0.66 | 0.49 | 0.75 | 0.45 | 0.80 |
| Seidl *et al.* | 0.65 | 0.62 | 0.68 | 0.51 | 0.78 | 0.46 | 0.81 |
| Ulrich *et al.* | 0.64 | 0.61 | 0.67 | 0.50 | 0.77 | 0.46 | 0.80 |
| Maudens *et al.* | 0.67 | 0.64 | 0.70 | 0.53 | 0.79 | 0.48 | 0.85 |

Table 4 B Calculated values of $C_o$ from $V_d$ in table 6A for a 90.6 kg male who drank two pints of 4 vol% beer (35.9 g ethanol). CI = confidence interval.

| Method | Calculated $C_o$ (mg/100ml) | 68% CI (mg/100ml) (Min, Max) | | 95% CI (mg/100ml) (Min, Max) | | 99% CI (mg/100ml) (Min, Max) | |
|---|---|---|---|---|---|---|---|
| Widmark (0.68) | 56 | 53 | 59 | 48 | 71 | 47 | 82 |
| Widmark (0.70) | 56 | 53 | 59 | 48 | 71 | 47 | 82 |
| Forrest | 60 | 57 | 63 | 51 | 76 | 47 | 82 |
| Watson (Age, Ht & Wt) | 63 | 59 | 65 | 53 | 82 | 50 | 88 |
| Watson (Age & Wt) | 64 | 60 | 66 | 53 | 81 | 49 | 88 |
| Seidl *et al.* | 61 | 58 | 64 | 51 | 77 | 49 | 86 |
| Ulrich *et al.* | 62 | 59 | 64 | 52 | 79 | 49 | 86 |
| Maudens *et al.* | 59 | 56 | 62 | 50 | 74 | 46 | 82 |